Introduction to Combustion MCL 343

Major Test (36 Marks)

$x\,dx$

1-D Energy Equation: $\rho v_x C_p \frac{dT}{dx} = \frac{d}{dx}\left(\lambda \frac{dT}{dx}\right) + \Delta h^o_{R_f} w_f$

$\lambda \frac{dT}{dx} \quad \frac{d}{dT}\left(x\frac{d}{d}\right.$

Fick's law $\dot{m}_i'' = Y_i \dot{m}'' - \rho D \frac{dY_i}{dr}$

$\frac{\lambda}{2} \frac{d}{dT}\left(\left(\frac{dT}{dx}\right)^2\right)$

Problem 1

Consider a spherical metal particle that burns on the surface and forms a nonvolatile oxide that immediately dissolves upon formation in the metal itself. The surface reaction and dissolving rates can be assumed to be infinitely fast when compared with the oxidizer diffusion rate. Take the surrounding fluid to be stagnant air and assume ρD = constant

(A) Draw the mass fraction profiles of all the relevant gas phase species present. **(1)**

(B) Derive an expression for the burning rate of the metal when the metal radius is r_s, assuming quasi-steady state. Take υ to be the mass-based stoichiometric coefficient for metal oxidation. **(5)**

(C) What is the magnitude and direction of the gas-phase velocity at a distance R (>r_s) from the particle center? **(2)**

Problem 2

Consider a constant volume spherical bomb (of radius R) used to measure the laminar burning velocity of a premixed gas mixture. A premixed flame is ignited at the center and propagates outward. The instantaneous location and velocity of the flame front are recorded as r and dr/dt. The pressure within the bomb rises with flame propagation and the instantaneous values of p and dp/dt are also recorded using a dynamic pressure transducer. S_u $\dot{m}_u$

(A) Argue that the laminar burning velocity is directly related to $\dot{m}_u$, the mass rate of consumption of the unburnt mixture. Write down the simple expression connecting the two. **(2)**

(B) Now perform mass balance on a control volume coinciding with the unburnt mixture at time t to show that $\rho S_u (4\pi r^2)$

$$S_u = \frac{dr}{dt} - \frac{R^3 - r^3}{3p\gamma_u r^2}\frac{dp}{dt}$$

The compression of the unburnt gases due to the flame propagation and the rising pressure can be assumed to be adiabatic (with exponent γ_u). **(5)**

Problem 3

Consider the two-zone differential model of laminar flame propagation into an unburnt mixture of density ρ_u.

(A) Solve the heat transfer differential equation in Zone I, the convection-diffusion zone, and argue that its length scale is α_u/S_u where α_u is the thermal diffusivity of the unburnt mixture. **(3)**

(B) Given that there exists a linear relation between species mass fraction and temperature in Zone I (given by $\frac{T_b - T}{T_b - T_u} = \frac{Y_u}{Y_{f,u}}$), evaluate the net mass flux of fuel into Zone II, the reaction-diffusion zone,

$(1+B)$

using your solution in part (A). How is your answer related to the net mass flux of fuel entering Zone I? **(3)**

(C) Sketch the product mass fraction profile in Zone I, providing actual numbers on the Y-axis **(1)**

Problem 4

Consider the two-zone differential model of laminar premixed flame. We will evaluate the Damkohler Number (Da) in Zone II in this problem. Da can be defined as the ratio of the kinetics rate to the convection rate.

The negligibly small fuel mass fraction in zone II is given as $Y_{f,R}$, whereas δ_R is the width and $w_{f,R}$ is the kinetics-based specific fuel consumption rate (kg/m^{3}s) in zone II. Also given are ρ_u, S_u, $Y_{f,u}$, ρ_b, S_b with their usual connotations.

(A) Express the convective mass flux of fuel into Zone II in terms of the given parameters **(1)**

(B) Express the net fuel consumption rate within Zone II in the same units as part (B) **(1)**

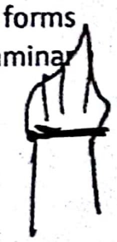
(C) Da is the ratio of your answers in parts (B) and (A). Show that $Da = \frac{Y_{f,u}}{Y_{f,R}}$ **(4)**

Problem 5

Consider the single film model of coal burning in air. Assuming infinite kinetics rate for combustion at the particle surface, evaluate Y_{N2} and Y_{CO2} at the particle surface assuming that the quasi-steady burning rate, $\dot{m}_c$, particle radius r_s, and ρD are known. **(4)**

Problem 6

(A) Consider a conical laminar premixed flame emanating from a Bunsen Burner. The flame surface forms an oblique angle with the flow so that the flow velocity normal to the flame surface matches the laminar burning velocity. The height of the conical premixed flame in such a case increases with



(I) The laminar burning velocity

(II) The exit flow velocity of the premixed gases emanating from the Bunsen Burner

(III) The exit temperature of the premixed gases emanating from the Bunsen Burner

(IV) The ambient pressure

(V) The diameter of the Bunsen Burner, keeping the exit flow velocity constant

Note: You are not required to give a reasoning for your choice(s) **(2)**

(B) A fixed-mass fluid element moving into the convection-diffusion zone (Zone I) of a laminar premixed flame gains sensible enthalpy via

(I) Heat Convection

(II) Heat Diffusion

Note: Provide a brief reasoning for your choice(s) **(2)**